

*Citation for published version:*

Harris, R & Roynon, J 2008, 'The Savill Garden Gridshell design and construction', Paper presented at 10th World Conference of Timber Engineering, Miyazaki, Japan, 2/06/08 - 5/06/08.

*Publication date:*  
2008

*Document Version*  
Publisher's PDF, also known as Version of record

[Link to publication](#)

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# The Savill Garden Gridshell Design and Construction

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## Summary

The paper describes the design and construction of the roof of the Savill Building. The structure is a timber gridshell, a technique presented at previous WCTE Conferences (2002[1] and 2004[2]). The timber for the Savill Building was harvested from the surrounding woodland. The form of the roof was derived from a simple geometric shape; the analysis and design checks were carried out using the Eurocode. Construction details and process, which developed from the techniques established on earlier buildings, are described.

## 1. Introduction

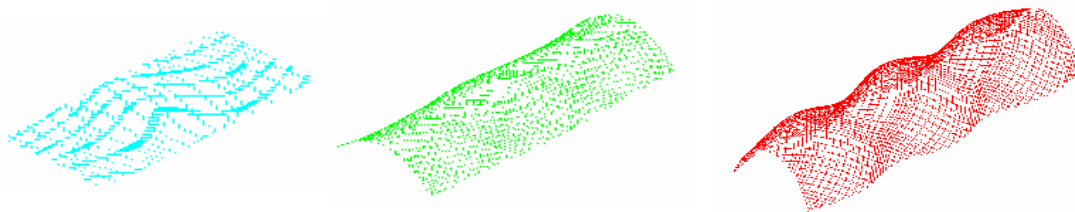


*Fig. 1 The Completed Downland Gridshell Building (Photo: Buro Happold / Adam Wilson)*

The first double-layer timber gridshell in the UK, for the Weald and Downland Open Air Museum (*Fig 1*) in Sussex, created international interest, quite disproportionate to its size, amongst architects, engineers and carpenters

## 2. Background

A shell is a three dimensional structure that resists applied loads through its inherent shape. If regular holes are made in the shell, with the removed material concentrated into the remaining strips, the resulting structure is a gridshell. The three dimensional structural stability is maintained by shear stiffness in the plane of the shell, achieved by preventing rotation at the nodes or by introducing bracing.



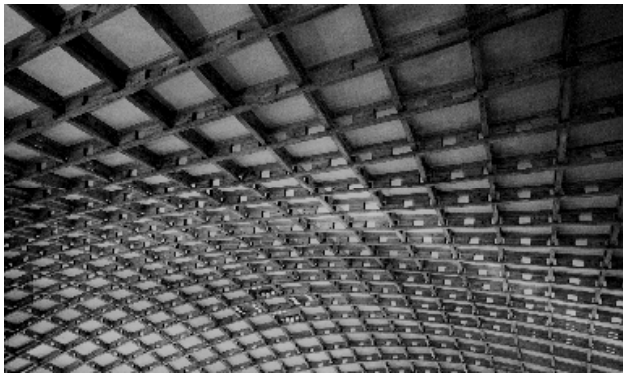
*Fig. 2 Computer simulation of forming timber gridshell*

Timber has low torsional stiffness and timber gridshells can be made by laying out a lattice as a flat mat and then pushed into shape (*Fig 2*). The very long timbers needed to make timber gridshells are fabricated by splicing shorter, defect-free pieces together. The word “lath” has been coined for these long timbers.

During forming, the timber lattice must allow rotation at the nodes and bending and twisting of its constituent laths. Once formed, shell action is accomplished by bracing, which triangulates the structure and provides in-plane shear strength. The first double layer gridshell was erected for the Bundesgartenschau in Mannheim, Germany, in 1975. For the Mannheim gridshell, crossed steel tension cables provided this bracing [3]. For the Downland Gridshell, the bracing was formed with timbers, acting as struts or ties that also supported the cladding. These diagonal timbers, running longitudinally in the lower half of the shell and transversely across the crown of the shell, were termed rib-laths. To save cost and make a more elegant structure for the Savill building, the cables were omitted and the plywood covering, which is needed to support the raised seam roof, was used instead.

### 3. The Savill Building Roof

Buro Happold have provided the structural engineering for the roof of the Savill Garden Building in Windsor Great Park, Berkshire.



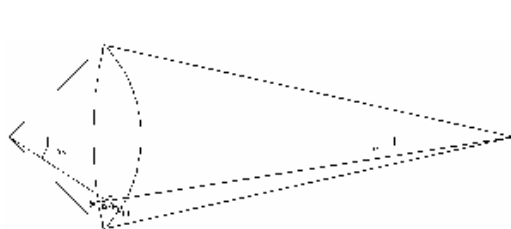
*Fig. 3 Timber Gridshell Roof*

The roof is 90m-long by 25 metres wide timber gridshell – the biggest in the UK. It is a three-domed, double curved structure of sinusoidal shape, and is expressed architecturally on the inside of the building (*Fig 3*).

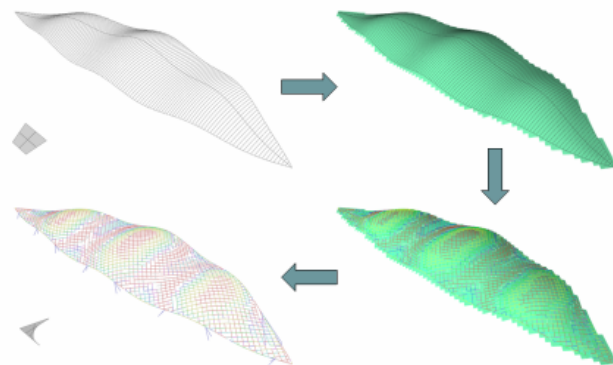
Buro Happold engineered the roof, working closely with HRW Engineers, the structural engineers for the whole building.

#### 3.1 Setting Out

There is a rigorous form underlying most structures in nature and, although this roof is not a natural organic shape, it has a clear underlying logic to its geometry.



*Fig. 4 Setting out plan*



*Fig. 5 Form finding and analysis model*

Dr. Chris Williams at the University of Bath carried out the initial form-finding for this project. Dr Williams has worked in the field of non-linear analysis of structures for many years; whilst working with Ted Happold at Ove Arup and Partners in the 1970s, he used both physical and computer models to carry out the analysis of the Mannheim shell.

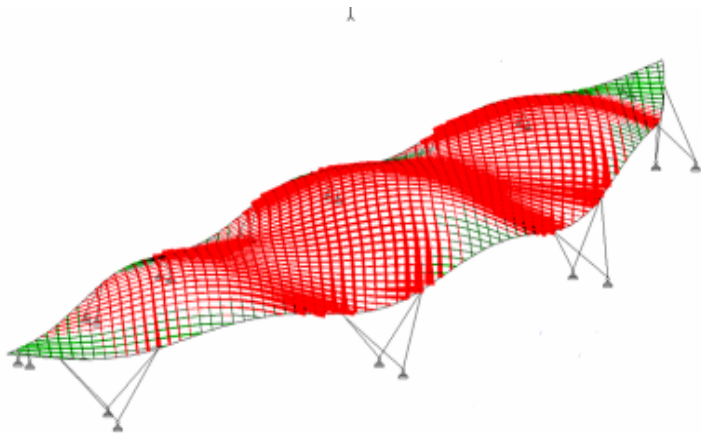
The theory behind the shape of the Savill gridshell is quite simple: on plan, the perimeter is set out using arcs of two intersecting circles (*Fig 4*). The curved centreline on plan is the midline between the circles. The centre line of the roof, in section, is generated by a sine curve, of varying amplitude, with its peaks and troughs at the tops of the domes and the bottoms of the valleys. The cross-section is then set out across the sinusoidal centre line as a series of parabolic curves of varying shape. Onto this surface a grid of equal length elements is generated. This was achieved by means of a programme written to define the shape as  $z = f(x, y)$  with a damped cosine wave in the x direction and upside down parabolas in the y direction.

By having a clear geometric basis to the surface shape, the architects and engineers could work together to adjust and agree a shape that met the aesthetic aspirations and practical constraints.

Onto this surface a grid of equal length elements is generated. The fitting of the equal mesh net on the surface is done using the fact that it is known where two opposite diagonal nodes of a little rhombus lie on the surface; the other two can be calculated. This problem is known as constructing a Chebyshev net.

### 3.2 Analysis

Once the formfinding model was agreed with the architect, the nodes were imported into a structural analysis model (*Fig 5*). Structural analysis was carried out using Robot 3D (*Fig 6*). The Eurocode for Timber Structures (BSEN 1995) was used to check the structural elements. The 3D model was then used by the fabricator to detail the structural elements.



*Fig. 6 Structural analysis model*

### 3.3 Structural Design



*Fig. 7 Steel support structure*

Load concentrations on the structure had to be carefully considered. Proposals for an all timber structure were considered but, in being true to the design competition concept and creating a dramatic structural statement, the long, high openings into the garden led to the introduction of steel tubes for the perimeter ring and the quadruped legs (*Fig 7*).

The timber structure springs from the perimeter ring. Kerto LVL (“Laminated Veneer Lumber”) fingers, bolted to the steel perimeter, are used to pick up load from the larch laths and progressively transfer of load from the shell to the legs (*Fig 8*).





*Fig. 8 Connection to perimeter tube*

In general the LVL fingers are hidden behind a soffit of plywood which extends beyond the glazed perimeter walls but, in places of very high load concentration, they can be seen pointing into the interior gridshell space.

To act as a shell, the structure must be strong and stiff in its plane. Initially the concept included steel cables to triangulate and thus brace the shell in its plane.

To save cost and make a more elegant structure the cables were omitted and the plywood covering, which is needed to support the raised seam roof, was used instead.

In supporting roof loads, this in-plane structure is just as important as the more visibly obvious laths. The Savill gridshell is made up of a regular one metre grid of 80mm x 50mm sections of larch timber. The three-domed shape is clad in oak. In construction, the height of the roof was adjusted at 200 points across the plan area to bring it to the desired shape.

The structure's own weight is easily carried by the timber and, with no other loads applied, the stresses in the laths and the plywood bracing are very small. More critical are the forces induced by severe wind and snow. In these design situations, the structural plywood helps transfer the forces through the domes or valleys of the roof, to the steelwork and foundations.



*Fig. 9 Completed Roof*

When snow collects on the roof, the plywood in the valleys acts in tension, inducing compression in the larch laths of the domes, which carry the load to the perimeter. When the wind blows through open doors (in a very strong wind it is possible that a door may blow open), the roof tends to lift off; the valleys go into compression and the domes into tension. In either state the timber shell works with the perimeter ring to carry the load to the quadruped legs.

### **3.4 Nodal Connection**

There are limitations on the tightness of curvature to which laths of a particular cross section can be bent. Hence the depth of lath required in a single layer gridshell to achieve relatively large spans may be too deep to permit bending of the flat lattice to a final shape that has tight radii of curvature. The solution to this problem is to utilise a double layer gridshell. For a lattice composed of four layers, effectively two single layer mats sitting one upon the other, the laths are of sufficiently small section to permit bending of the lattice into the desired geometry. Upon completion of forming, timber shear blocks are positioned between the lath layers and fixed with screws. These transfer horizontal shear between parallel layers and endow the lattice with the properties of a deeper section. The potential for this type of system is huge; multi-layered lattices can be utilised to achieve ever-increasing spans.

For the Downland and Mannheim gridshells all four laths were bent together [4] [5]. For the Savill Building, the bottom two laths were bent into shape, then the shear blocks were screwed into positions. The upper two laths were positioned over the shear blocks and screwed into place. This technique enabled greater spacing of the layers than achieved on previous gridshells, leading to greater out-of-plane strength and stiffness.

### 3.5 Timber Sourcing



*Fig. 10 Felled Larch at Windsor Great Park (Photo – Steve Corbett GOCC)*

The timber used in the structure has all come from the Crown Estate's commercially managed (and Forest Stewardship Council-certified) woodland in Windsor Great Park (*Fig 10*). It was very carefully chosen to ensure the quality and quantity of timber was sufficient. This sourcing process, which began in 2003, was carried out in parallel with structural tests of the wood which informed the structural design process and was critical in determining lath size and spacing as well as the quality of the bolted joints and screwed shear blocks.

Further selection of the wood, into high- and low-grade timbers, was made to ensure the critical structural members, such as the long lengths which carry the internal loads to the perimeter, are of necessary strength. Other elements, such as the infill blocks, are safely made of lower grade timber.

The timber was optimised using the GreCon Dimter Opticut 101 mechanised saw. Each length of larch was visually inspected by a skilled carpenter to identify knots, unacceptable slope of grain and other defects.

Visual grading entailed systematically marking the timber with a fluorescent crayon. The Opticut 101 has an optimisation computer that reads the fluorescent crayon marking, cuts out the defect and sorts, in accordance with the designated grade. Exact logging of the production data was also possible; this showed that the highest grade material ranged in length from 0.3m to 1.4m with average segment being 0.6m long.

Finger jointing was performed using the GreCon Dimter Supra finger-jointing machine. This is a continuous feed system. Fingers were cut simultaneously into the ends of the larch segments and the Collano Purbond HB 530 polyurethane adhesive was applied with the FLANK JET system that combs the adhesive onto the fingers. The segments were then aligned and pressed together at a pressure of 4 N/ mm<sup>2</sup>, on the 50 x 35mm section, to form 6m lengths.

The laths and finger joints were tested in a four point bending test in accordance with sample dimensions given in BS EN 408:1995: Timber Structures – Structural Timber and Glue laminated timber – Determination of Some Physical and Mechanical Properties. The samples were tested green and not conditioned to the requirements given in BS EN 408:1995. At the early stages of the project, a whole series of finger joint testing was undertaken examining a range of variables including capacity about both axes, performance of different adhesives and effect of different production pressure.

For the production stage, a quality control system was implemented to ensure the effectiveness of the finger joints. Quality control testing was carried out in two stages, pre-production tests and batch sampling. The results of these tests enabled a statistical analysis in accordance with EC5 Annex A, Section A2: 'Determination of 5-Percentile Characteristic Values from Test Results and Acceptance Criteria for a Sample'. The pre-production tests determined the 5-percentile characteristic bending strength of the finger joints, and coefficient of variation for the running production control. The batch testing ensured that the probability of accepting a sample with an ultimate bending strength less than the desired 30N/mm<sup>2</sup> was within acceptable statistical limits set out in EC 5 Annex A.

### 3.6 Site Jointing

The next stage in the process was to join the 6m lengths of 'improved' timber to produce continuous laths up to 37m long for the lattice laths and 50m long for the longitudinal rib laths. This work was carried out on site under the protection of a polytunnel. The 6m lengths were joined



using scarf joints with a slope 1 in 7. The slope of 1 in 7 gives the scarf joints a glue-line area the same as that for the finger joints.



*Fig. 11 Scarf Jointing on site (Photo: Buro Happold/Mandy Reynolds)*



*Fig. 12 Off-site Finger Joints (Photo: Steve Corbett of GOCC)*



*Fig. 13 Fixing sheer blocks (Photo: Buro Happold/Adam Wilson)*

The site scarf joints were made up in an environmentally controlled workshop. (Fig 11). There is an interesting contrast in two jointing methods used; the finger joints are the latest timber joining technology whereas the scarf joint has been used for centuries.

The gridshell lattice would require 6000 linear metres of lath; considering that individual pieces of graded lath averaged 0.6m in length this represented 10,000 finger joints. Although the timber had to be transported to the specialist machine the total weight was only 6 tonnes. Such a small quantity is easy to transport in one load.

The advantage of using ‘improved’ larch laths was that the quality of the material was maximised very quickly and cheaply with minimum wastage.

The same jointing method as that used at the Downland Gridshell [6] was used for the Savill Building Gridshell; the Windsor Great Park larch being sawn, finger jointed and planed off-site (Fig 12). The result was 10,000m of high quality larch and another 10,000m of lower grade timber, all in six-metre lengths. The higher grade material was scarf jointed into 36 metre lengths in a temporary carpentry workshop on site. These formed the major lengths that transfer the structural loads and make up the grid. The lower grade timber was used for shear blocks and packing pieces. The result was very little wastage and efficient use of the trees.

Unlike the Downland Gridshell, at Savill, because the shell did not have to wrap around to form the walls, it was erected by manipulating the bottom two layers into position and then screwing the shear blocks down (Fig. 13) before adding the top two layers over the top. In this way it was possible to create extra depth to the overall shell.

More than 20km of 80mm x 50mm larch timber is used in the gridshell. The roof structure weighs 30 tonnes – much less a similar roof in concrete, reducing the loads on the quadruped legs and foundations.



*Fig. 14 Fixing oak cladding boards*

On top of the gridshell is 160mm of insulation, covered by an aluminium roof system and a profiled standing-seam skin which is the waterproof layer and support for the oak rain-screen (*Fig. 14*). Oak was specified for its natural resistance to the elements and for the silvery-grey look it will assume as it weathers.

The confluence of the structural engineering knowledge and analytical and detailing capability of Buro Happold, the design flair of the architect, Glenn Howells Architects and The Green Oak Carpentry Company's remarkable three-dimensional understanding of wood, combined with very high levels of organisational skill and the application of years of craft-based experience, has enabled this structure to be realised.



*Fig. 15 Completed building (Photo: Warwick Sweeney)*

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